SURFACE PROPERTIES OF MICROMACHINED POLYCRYSTALLINE SILICON STRUCTURES

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This report documents the results to date of the surface characterization of micromachined polycrystalline silicon structures project. In particular, polysilicon flaps fabricated in the MUMPs 36 and 37 runs at Cronos, a JDS subsidiary, were investigated. Atomic force microscopy (AFM), scanning electron microscopy (SEM), and electron dispersive spectroscopy (EDS) were used to determine the surface topography and chemical composition of the surfaces. Fabricated die were dried after the removal of the sacrificial oxide layers using two methods: air and supercritical CO_2 drying. The effects of release etching on the surface roughness were also studied. The layout of the flaps on the chip and flap design will first be presented. Then, the AFM and EDS results for the air dried die will be discussed. Next, the pre- and post-release AFM scans of the second structural layer subject to a HF etch are shown. The AFM and EDS results for the supercritical CO_2 dried sample are then described. Finally, some initial conclusions are presented.

A. MUMPs chip layout and flap design

The section of the die containing the polycrystalline flaps investigated in the current study is shown in Fig. 1. This is the layout for the MUMPs 36 run. The upper three rows of flaps are made of the second structural layer in the MUMPs process (poly2), and the lower three rows are made of the first structural layer (poly1). The standard thickness of poly1 and poly2 are 2 μm and 1.5 μm, respectively. The flaps are either 500 μm by 500 μm, 200 μm by 200 μm, or 100 μm by 100 μm. The flaps are hinged on one side (the left in Fig. 1) to allow them to be flipped. They also have a cantilever beam that can be buckled and used to assist in flipping the flaps underneath the flaps or a side flap. Additionally, the flaps on the left half of side of Fig. 1 are not anchored to the substrate in anyway. The hinges are the only structure holding them down. Thus, during release processing they may flip or float in the liquid at an angle. To have some flaps which remain stationary during release, the structures on the right in Fig. 1 have thin tie-down beams which need to be broken prior to flipping the flaps. There are etch holes and dimples on the flap surfaces to aid in the sacrificial layer and prevent surface adhesion, respectively. The etch holes on all plates are spaced 40 μm apart. Dimples are spaced 20 μm apart. These plates were generated using the palette in MEMS-Pro. The MUMPs 37 chip contained similar flaps but fewer in number due to space constraints.

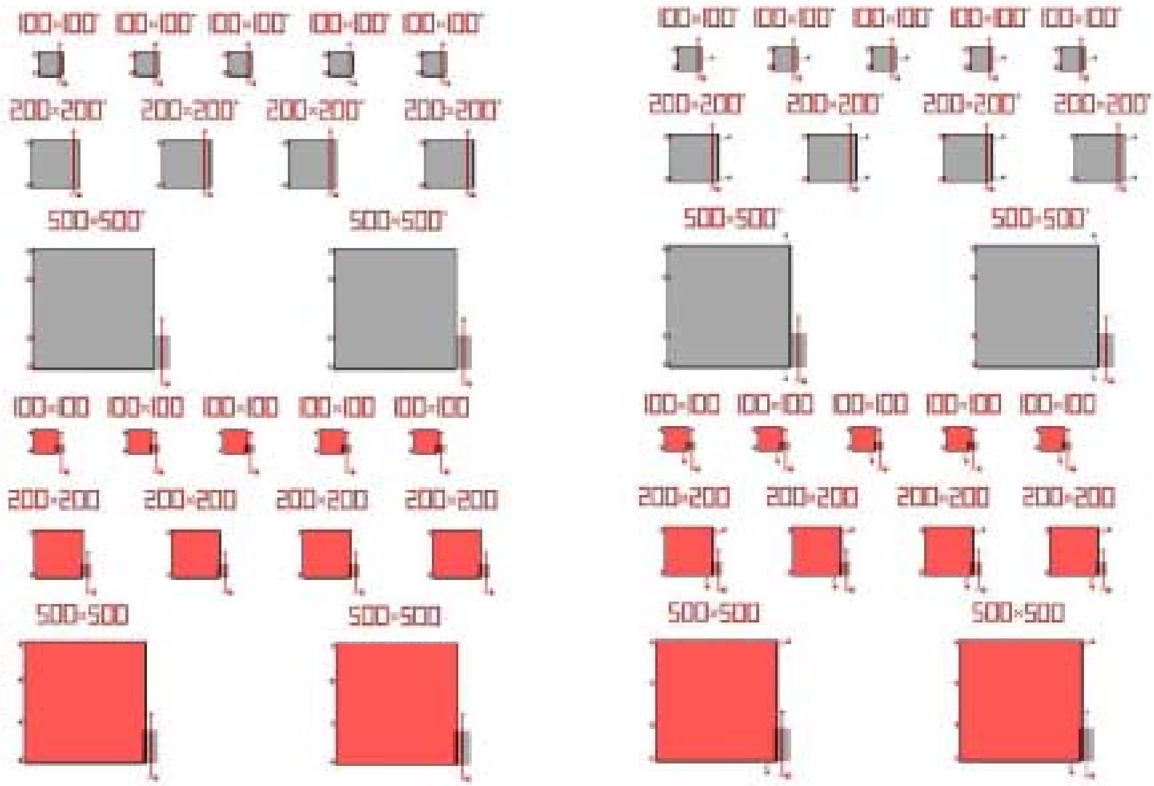


Figure 1: Layout of the section of the MUMPs 36 chip containing the flaps

Poly1 flip-over plates

Schematic of a top view of typical test structure in this array:

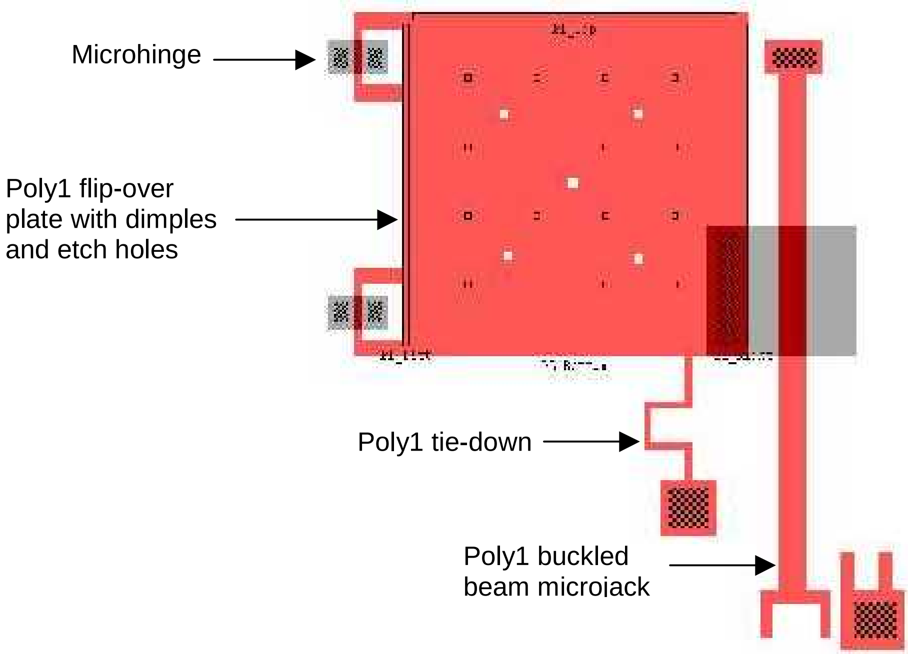
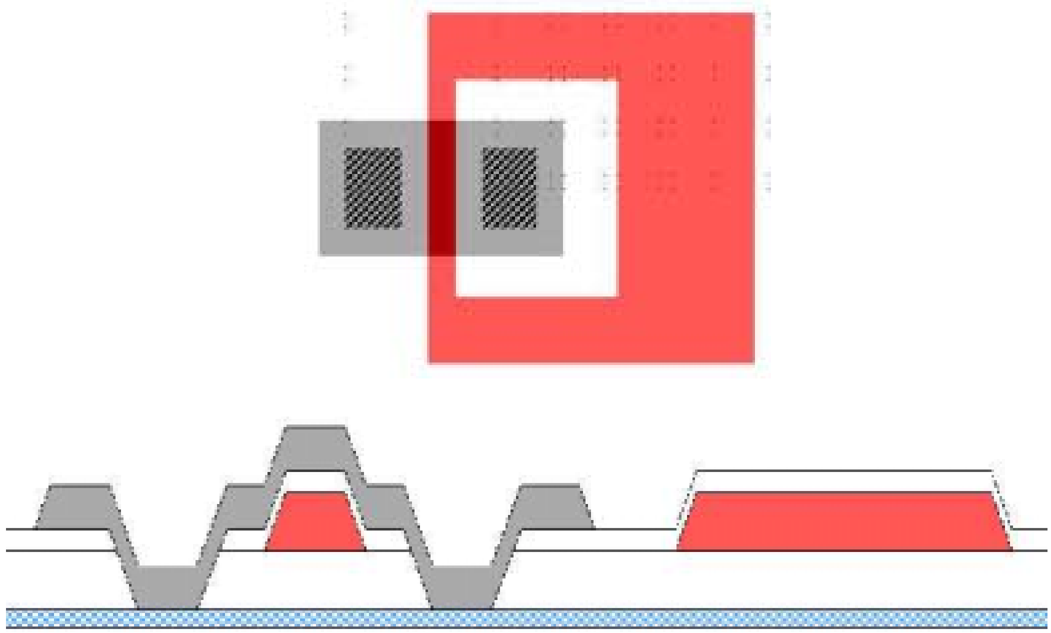
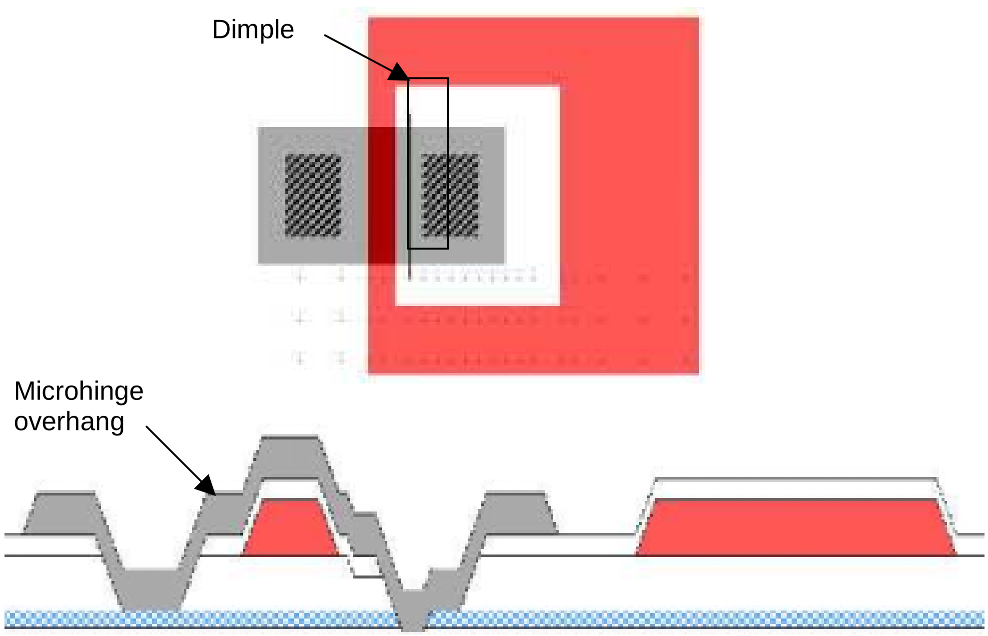


Plate dimensions vary from 100 µm x 100 µm to 500 µm x 500 µm. The tie-down is supposed to be broken after release etching. Microjacks are used to help lift the poly1 plate -- using a probe the free end is pushed towards the anchored end, buckling the beam, and lifting the poly1 tab. Then a second probe can then be safely slid under the plate to complete rotation about the hinges.

There are several types of microhinges in this array of test structures. Shown above is the basic substrate hinge. Top view and side view (showing sacrificial oxides) are shown below. Hinge consists of a poly1 plate and hinge pin and a poly2 staple.



Modified substrate hinges are also included in this array. These consist of dimple patterned through the hinge to prevent the poly1 hinge pin from getting pegged under the poly2 staple overhang (on one side) after release etching. The modified substrate hinges are only used with the poly1 flip-over plates without tie-downs.



Poly2 flip-over plates

Similar to poly1 flaps, only now the plates are poly2. Note -- these plates have dimples just like the poly1 plates. Only basic hinges used with this test structure.

Top view of typical test structure in this array:

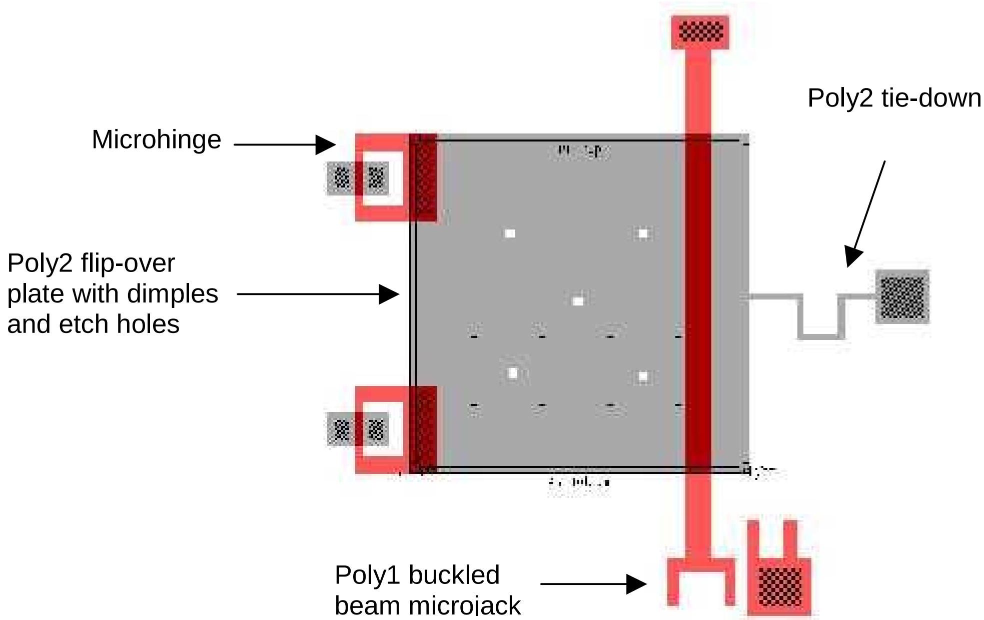
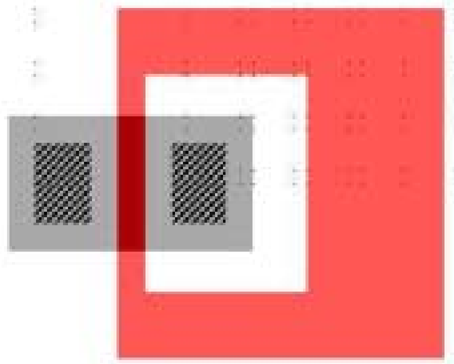
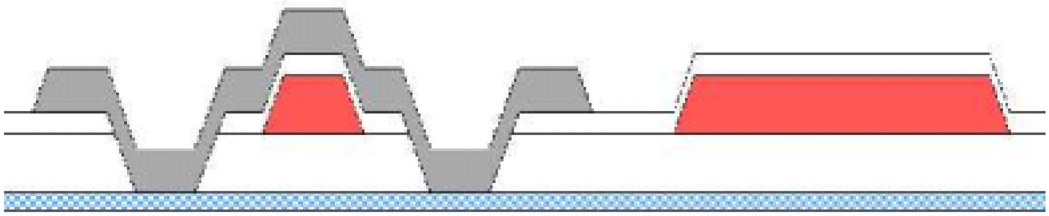


Plate dimensions vary from 100 µm x 100 µm to 500 µm x 500 µm. The tie-down is supposed to be broken after release etching. Microjacks are used to help lift the poly1 plate -- using a probe the free end is pushed towards the anchored end, buckling the beam, and lifting the poly1 tab. Then a second probe can then be safely slid under the plate to complete rotation about the hinges.

Shown below is the basic substrate hinge. Top view and side view (showing sacrificial oxides) are shown below. Hinge consists of a poly1 plate and hinge pin and a poly2 staple.





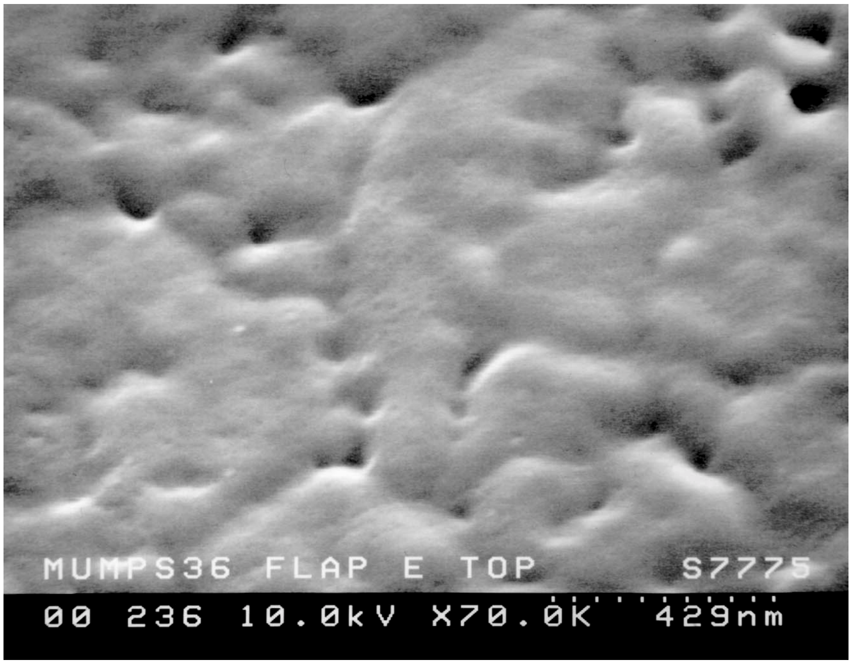
B. HF release and air dry

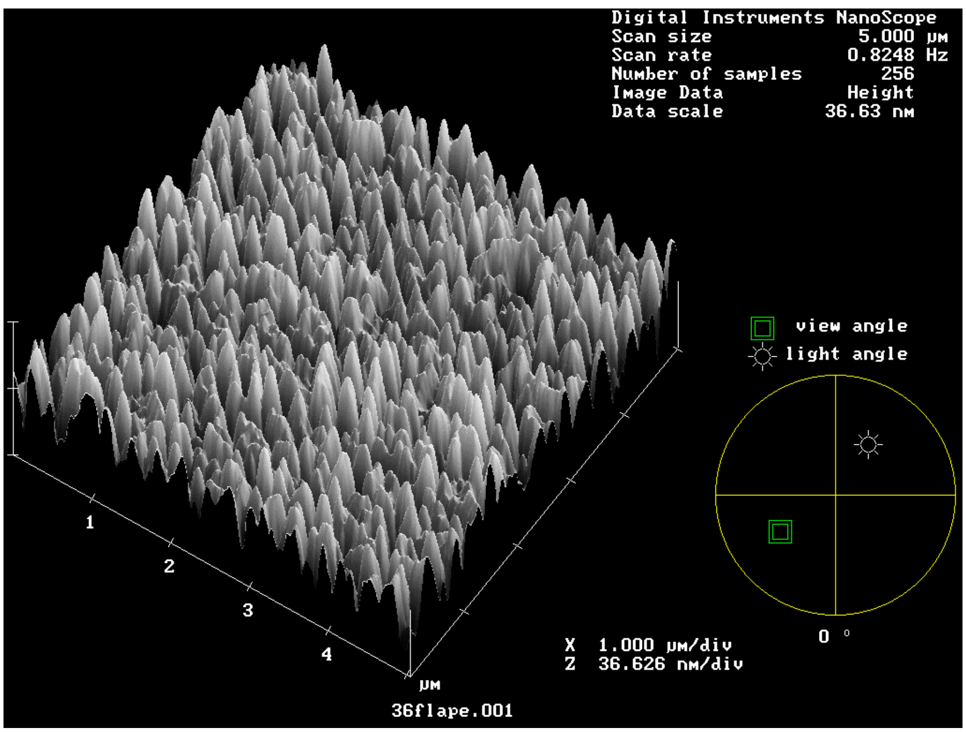
The surfaces of die with the structures released through an HF etch, water rinse, methanol dip, and air dry were characterized using an optical microscope, AFM, SEM, and EDS. For the roughness data calculated from the AFM scans, the mean roughness for an image, R_a, was defined as the arithmetic average of the absolute values of the surface height deviations measured from the mean plane. The formula for calculating the image mean roughness is

$$R_a = \frac{1}{N}\sum_{j=1}^{N}|Z_j|$$

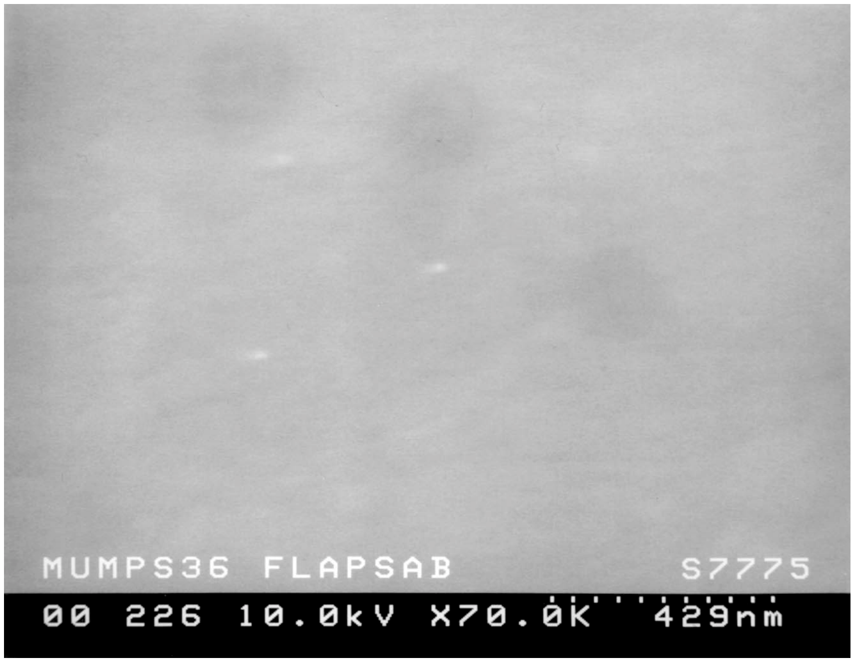
where Z_j is the current difference between the height and the mean plane and N is the number of points in the image. The rms roughness for an image, R_q, is defined as the root mean square average of height deviations taken from the mean data plane and is calculated according to

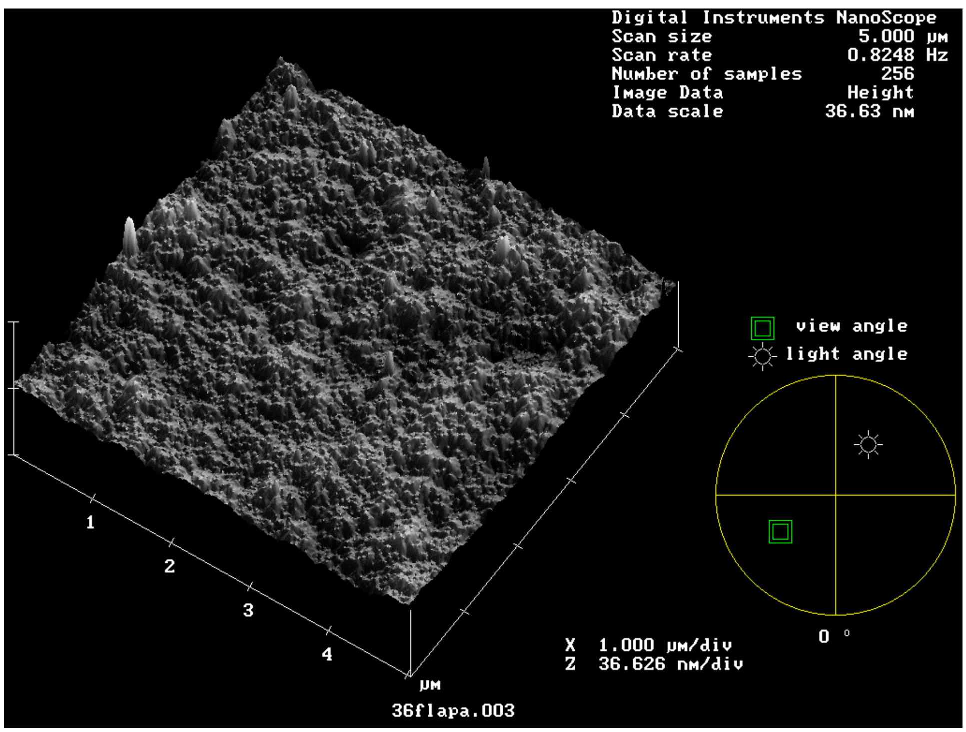
$$R_q = \sqrt{\frac{\sum Z_i^2}{N}}$$



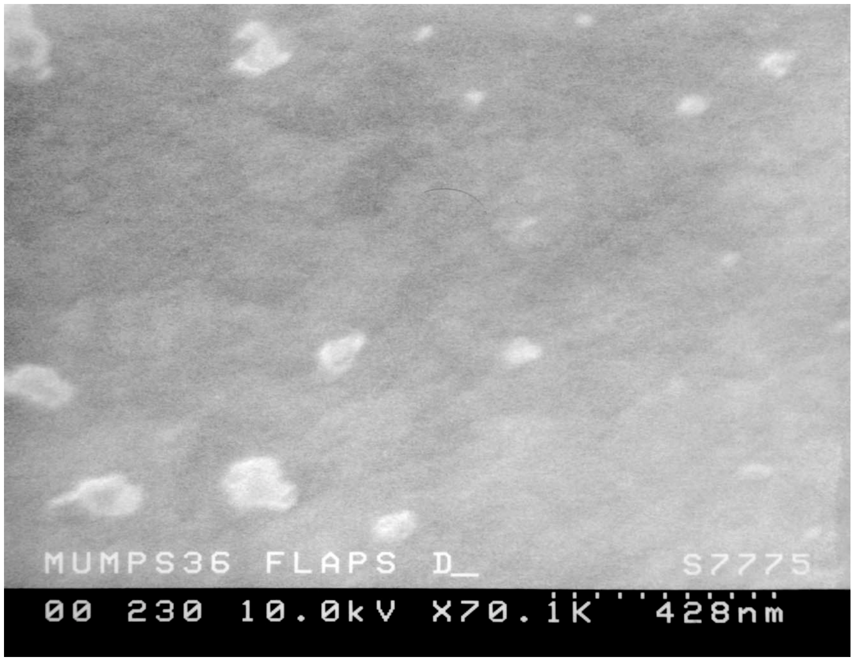


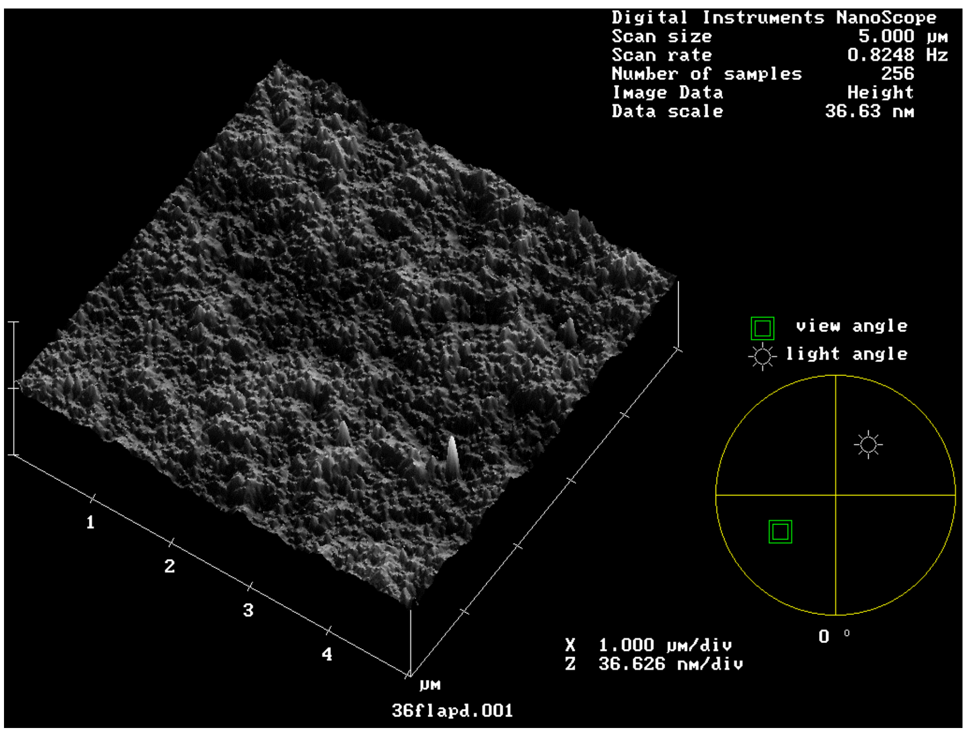
SEM (above) and AFM (below) images of the upper surface of a poly1 plate. The surface is rough and fairly clear of residues. The top of the poly1 layer had roughness measurements of R_a of 7.20 nm and R_q of 9.05 nm.



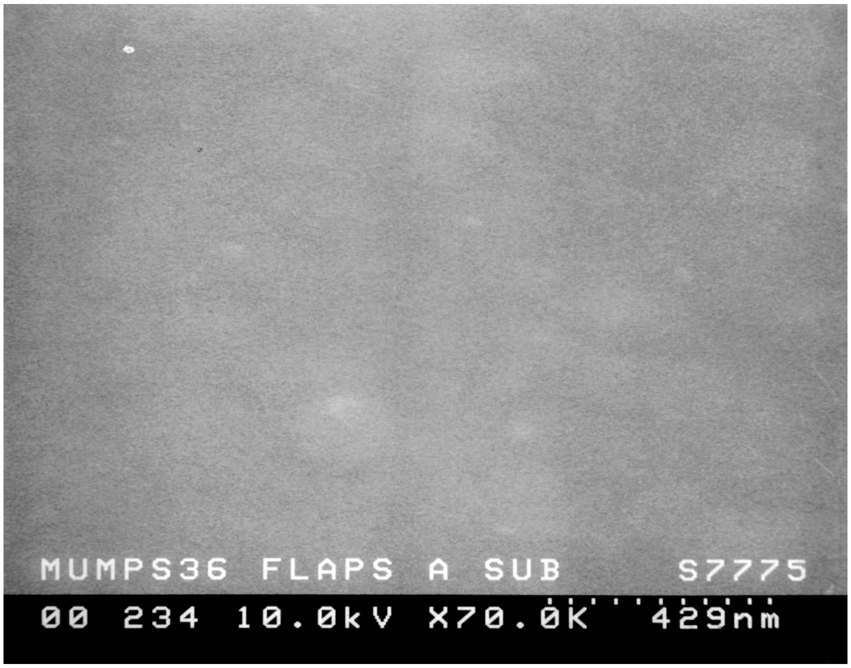


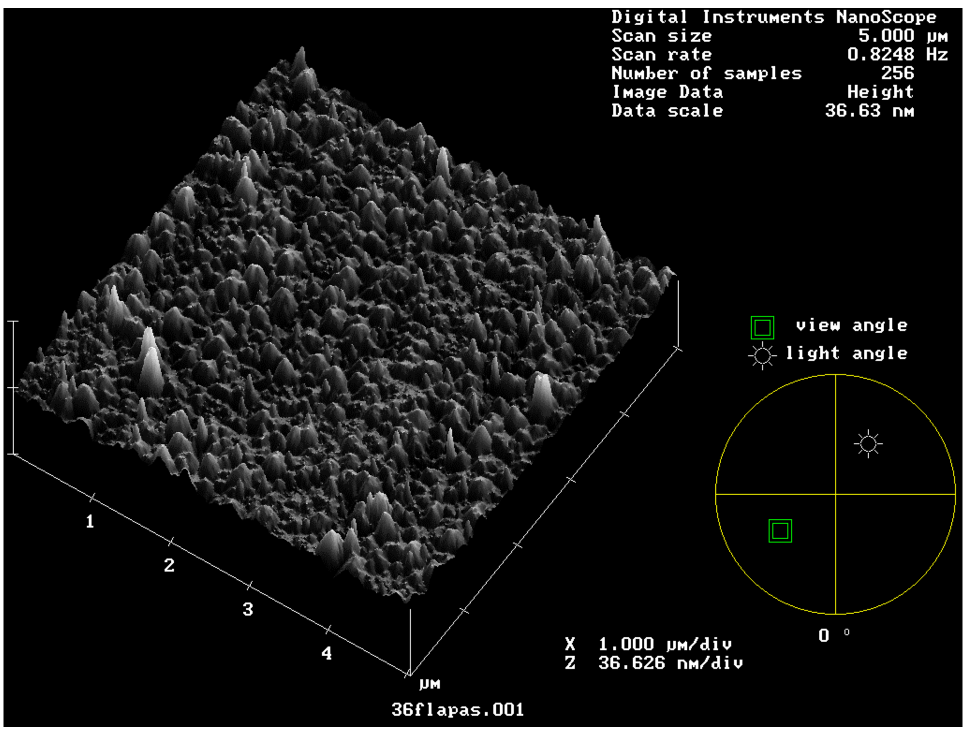
SEM (above) and AFM (below) images of the bottom surface of a poly1 plate without a tie-down structure. The surface is smooth and fairly clear of residues. The bottom of the poly1 layer had roughness measurements of R_a of 1.43 nm and R_q of 1.87 nm.



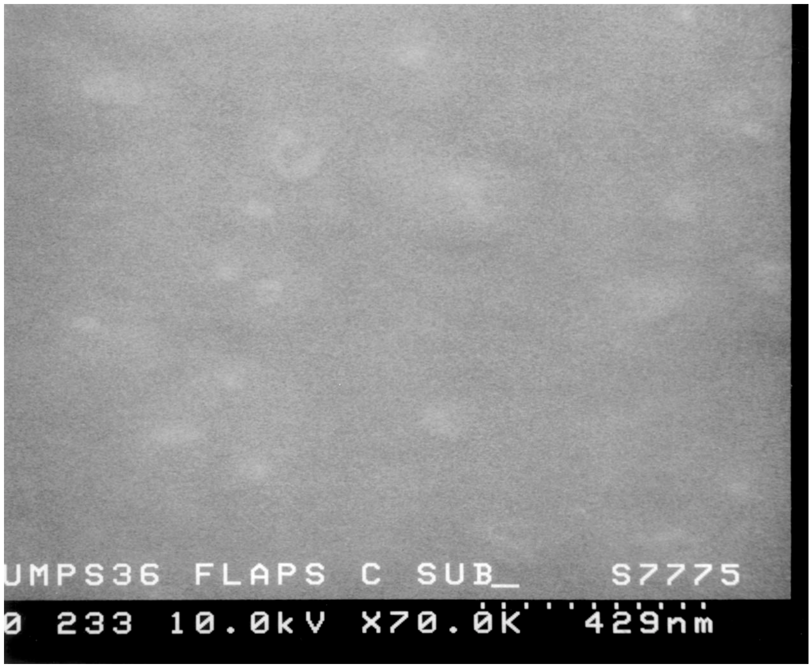


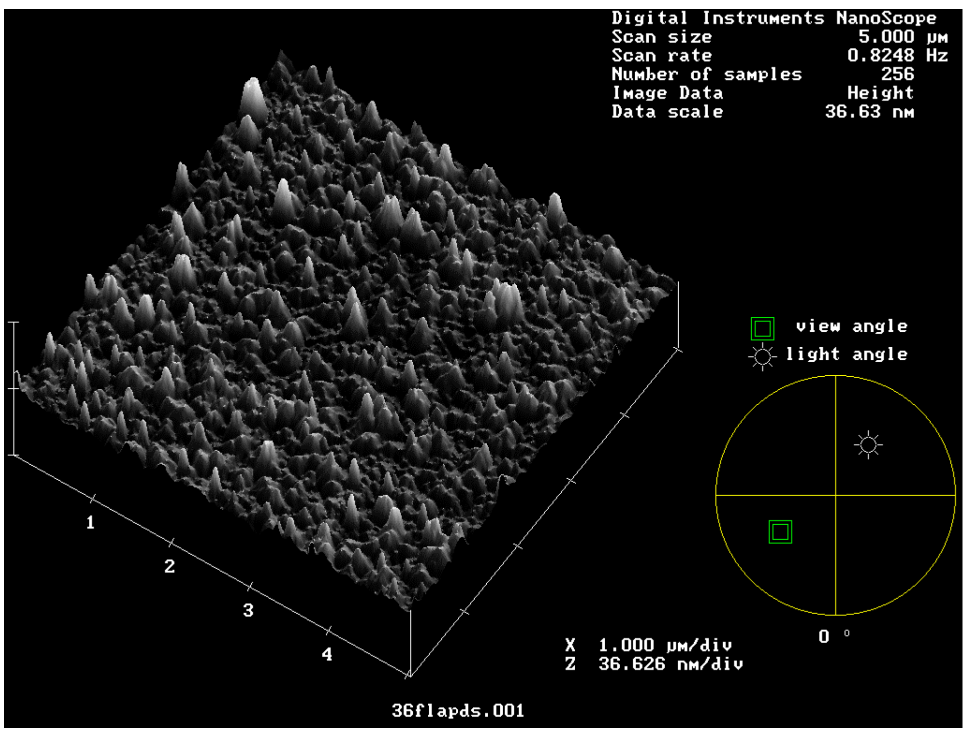
SEM (above) and AFM (below) images of the bottom surface of a poly1 plate with a tie-down structure. The surface is smooth and but has significant residues. The bottom of the poly1 layer had roughness measurements of R_a of 1.54 nm and R_q of 1.97 nm.





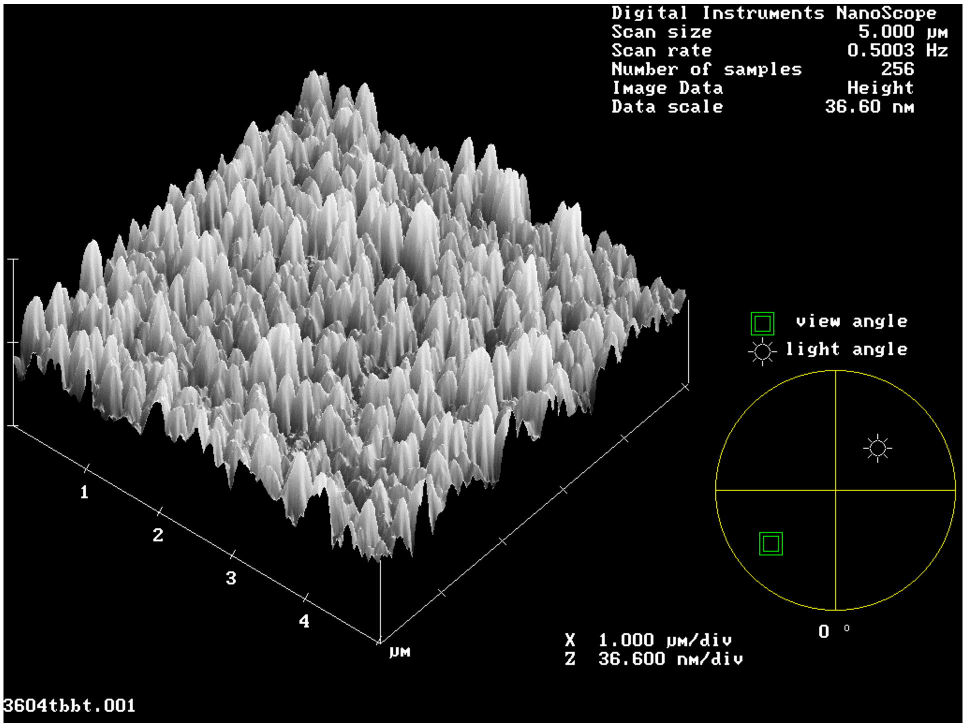
SEM (above) and AFM (below) images of the silicon nitride layer below a poly1 plate without a tie-down structure. The surface is rougher than the underside of the poly1 and fairly clear of residues. The roughness measurements were R_a of 2.03 nm and R_q of 2.71 nm.

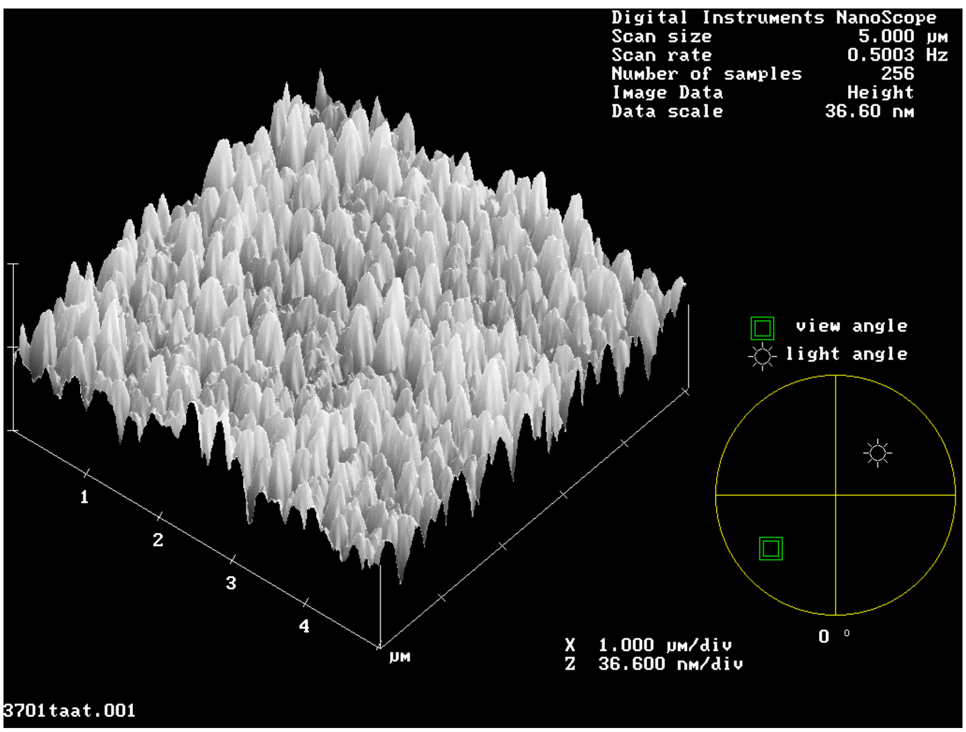




SEM (above) and AFM (below) images of the silicon nitride layer below a poly1 plate with a tie-down structure. The surface is rougher than the underside of the poly and has significant residues. The roughness measurements were R_a of 2.08 nm and R_q of 2.83 nm.

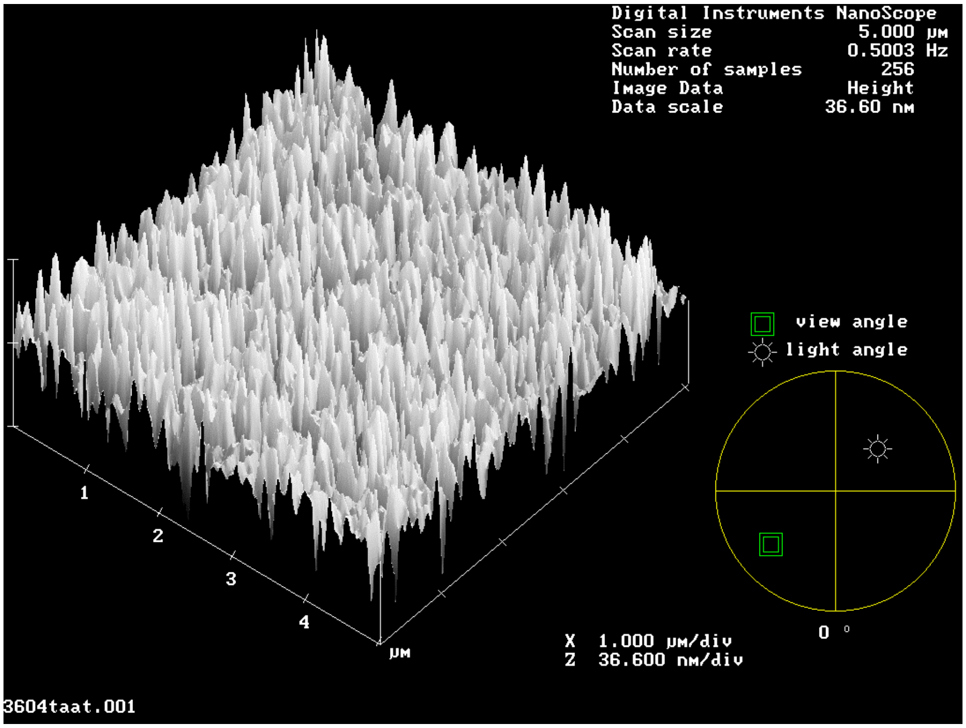
Pre-Release data for poly2 flaps

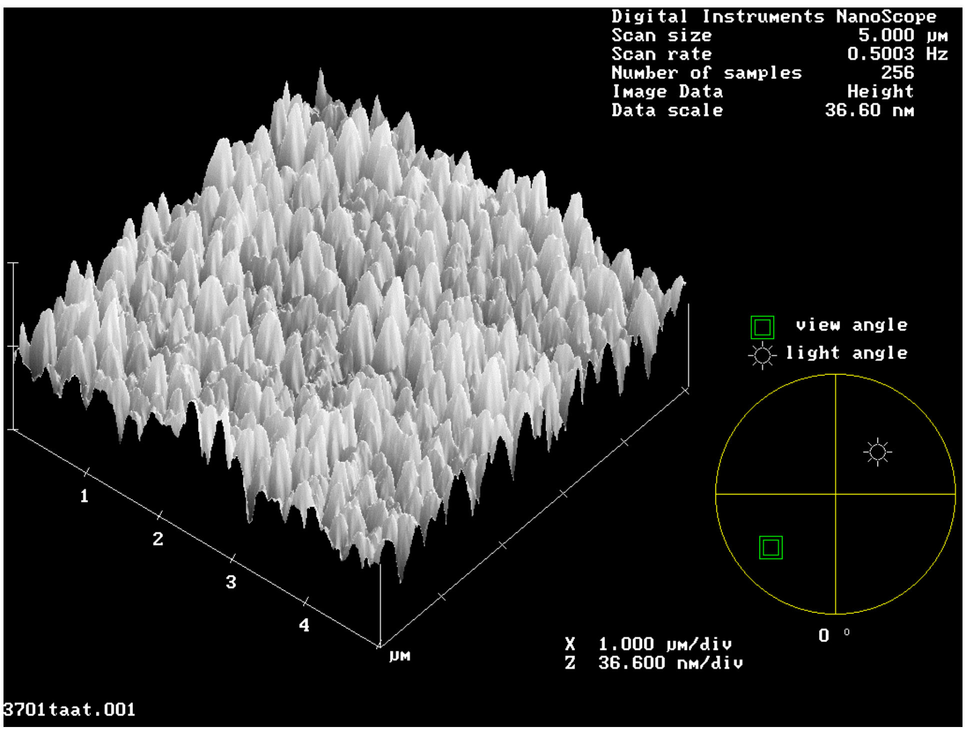




AFM images of the top of a poly2 layer prior to sacrificial layer removal for a MUMPs 36 (above) and MUMPs 37 (below) chip. The average roughness for MUMPs 36 poly2 flaps was R_a of 4.92±0.18 nm and R_q of 6.10±0.28 nm. The average roughness for MUMPs 37 poly2 flaps was R_a of 5.61±0.21 nm and R_q of 7.11±0.22 nm.

Post-Release data for poly2 flaps





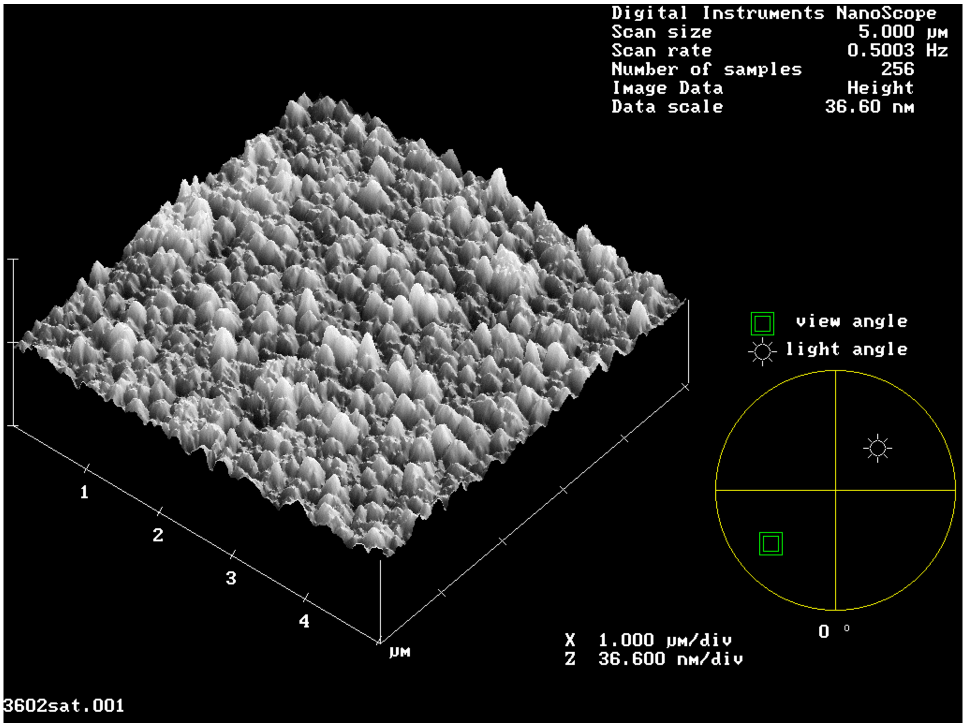
AFM images of the top of a poly2 layer after sacrificial layer removal for a MUMPs 36 (above) and MUMPs 37 (below) chip. The average roughness for MUMPs 36 poly2 flaps was R_a of 7.55±0.13 nm and R_q of 9.57±0.11 nm. The average roughness for MUMPs 37 poly2 flaps was R_a of 7.07±0.37 nm and R_q of 9.03±0.74 nm. The increase in surface roughness due to the release was in the range of 1.5 to 4 nm.

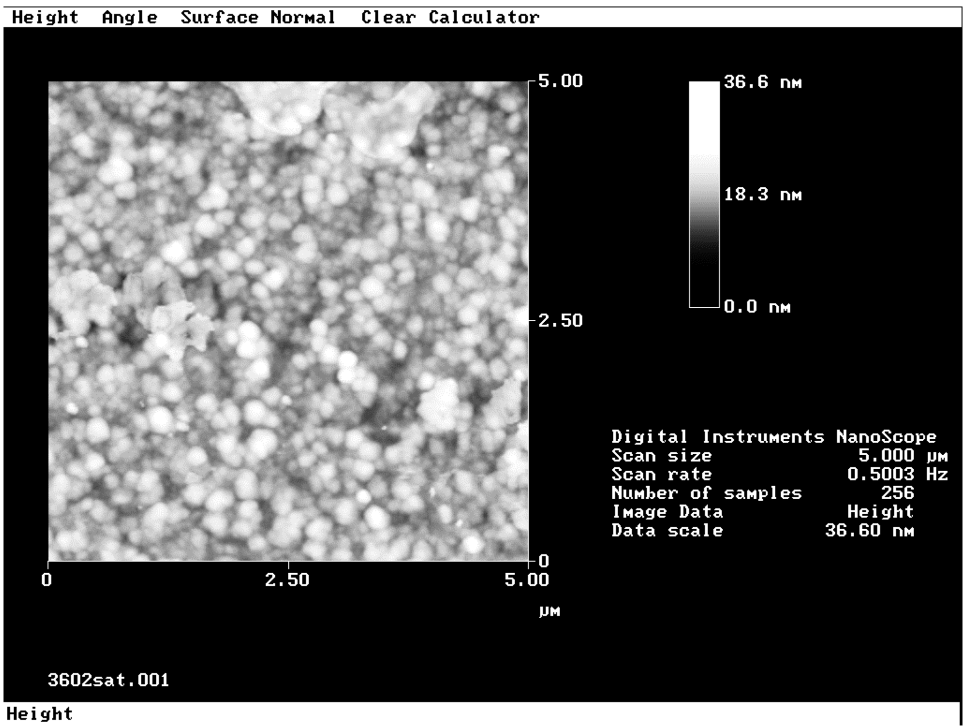
C. CO_2 supercritical dry

SEM of the bottom of a poly1 flap (above) and the silicon nitride under a flap (below) for a die released with a CO_2 supercritical dry process. The surfaces are in general pretty clean.

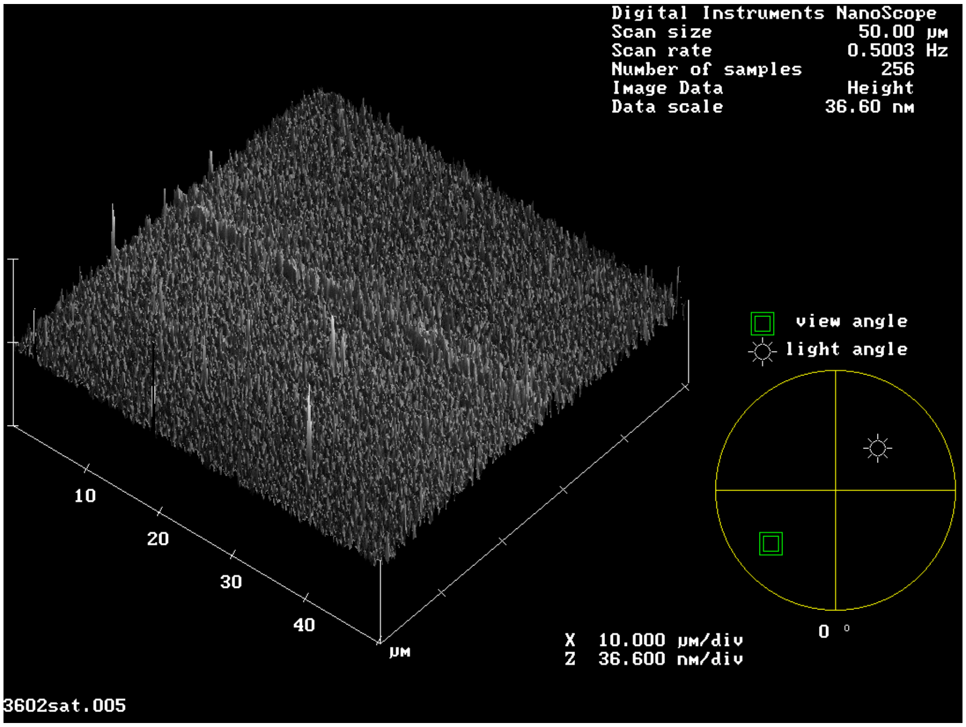
SEM images of residue spots on the bottom of a poly1 flap for a die released with a CO_2 supercritical dry process. EDS showed silicon and fluorine with the fluorine peak being relatively strong.

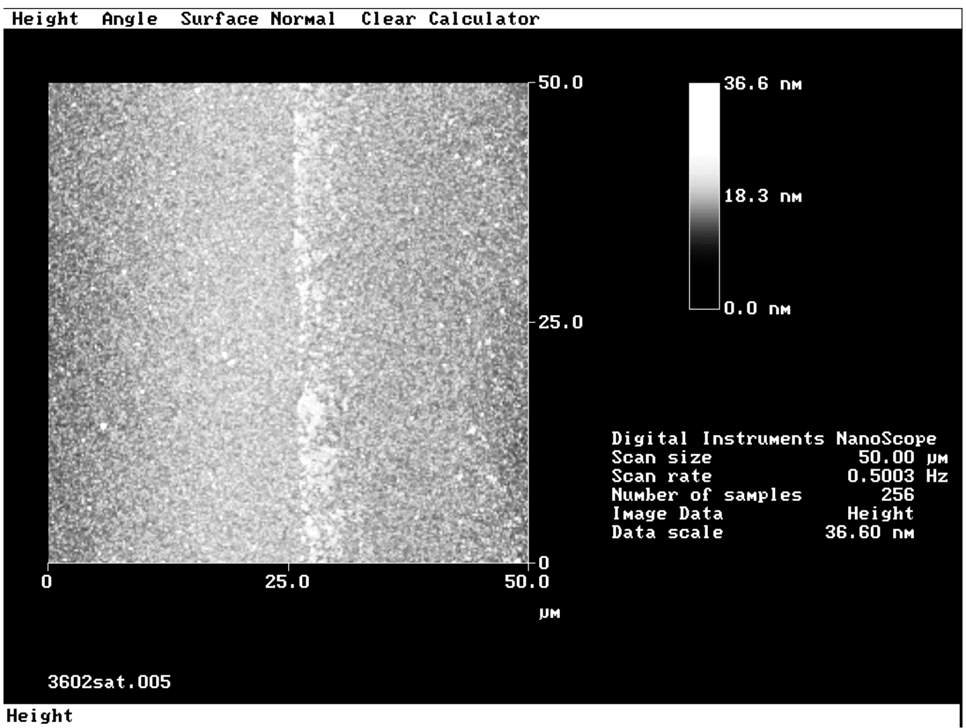
SEM images of residues on the silicon nitride layer below a poly1 flap for a die released with a CO_2 supercritical dry process. EDS of the top residue showed silicon, nitrogen, oxygen, sodium, and sulfur.



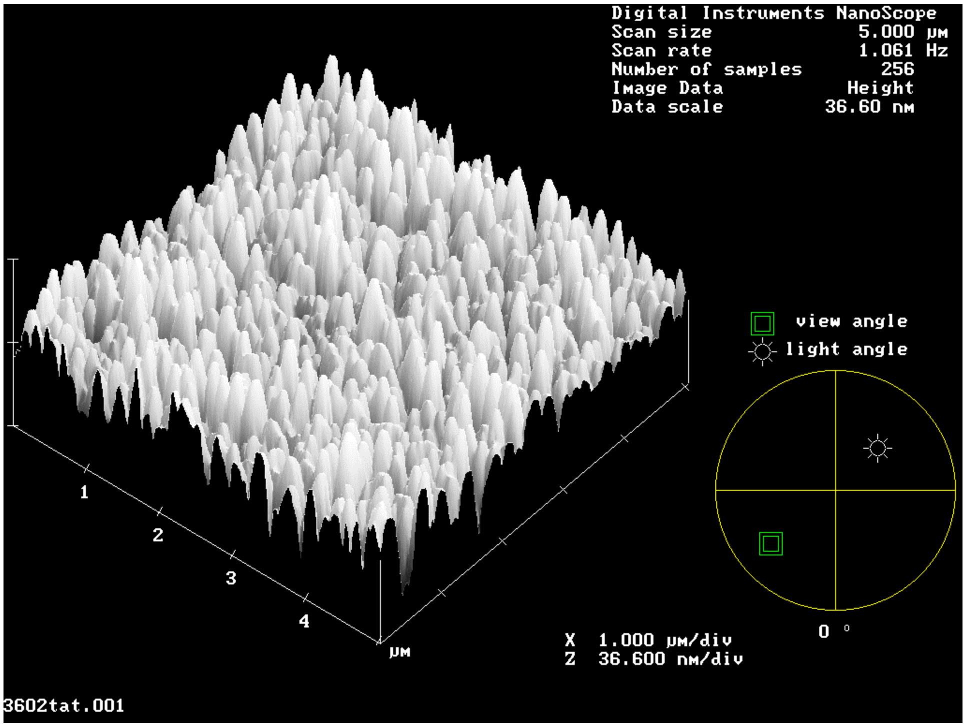


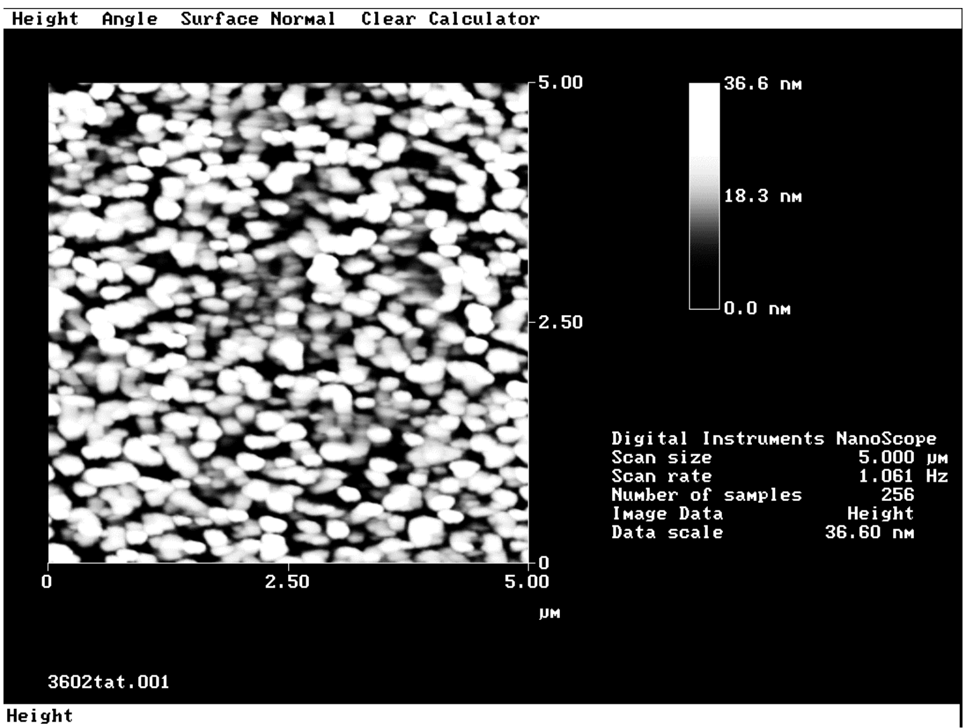
AFM images of the silicon nitride layer under a poly1 flap of a die released with a CO_2 supercritical dry process. Spots of residue are visible on the surface. The roughness measurements are R_a of 1.89 nm and R_q of 2.38 nm.



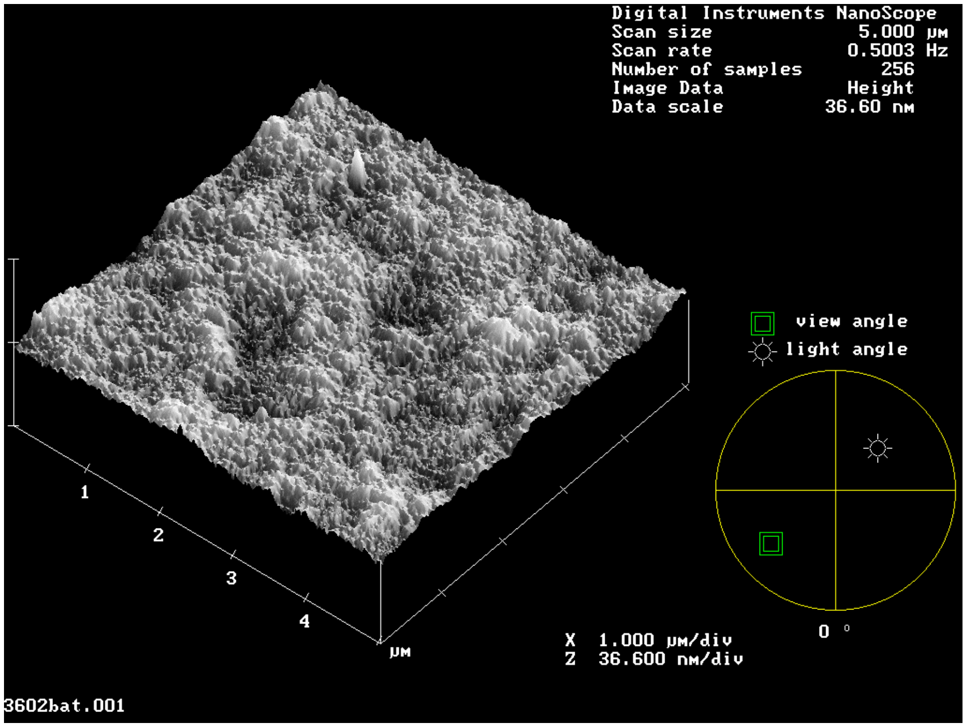


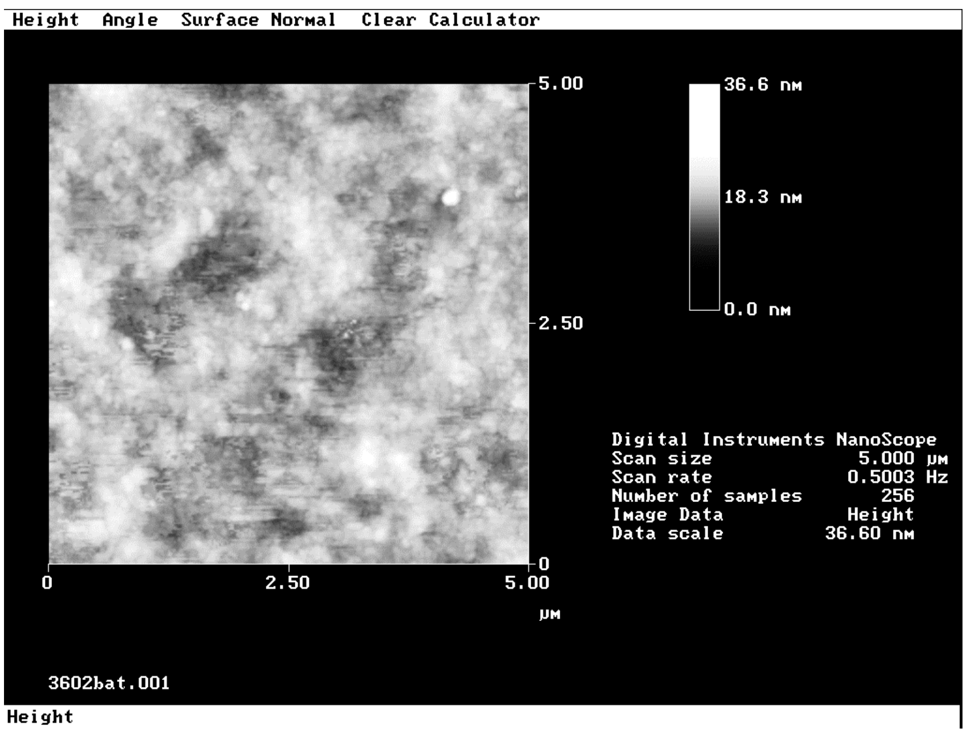
AFM images of the silicon nitride layer under a poly1 flap of a die released with a CO_2 supercritical dry process. A line of residue is visible on the surface. The roughness measurements are R_a of 1.72 nm and R_q of 2.30 nm.





AFM images of the upper flap surface of poly1 flap for a die released with a CO_2 supercritical dry process. The surface appears fairly clean. The roughness measurements are R_a of 7.03 nm and R_q of 9.00 nm.





AFM images of the lower flap surface of poly1 flap for a die released with a CO_2 supercritical dry process. The surface appears fairly clean. The roughness measurements are R_a of 1.51 nm and R_q of 1.93 nm.

D. Preliminary Conclusions

For the MUMPs fabrication process, the smoothest surface of those investigated is the lower surface of the polysilicon with R_a of around 1.44±0.11 nm and R_q of 1.91±0.09 nm. The silicon nitride layer has roughness measurements of R_a of around 2.02±0.12 nm and R_q of 2.79±0.15 nm. Since these surfaces are so smooth it is not surprising that there is a stiction problem for polysilicon structures on silicon nitride substrates. The top of the poly1 layer has roughness measurements of R_a of around 7.38±0.18 nm and R_q of 9.29±0.24 nm.

For an air-dry release process the presence of tie-down structures on a large plate appears to increase the amount of residue deposited on bottom of the polysilicon flap and substrate underneath it. The residues contain fluorine according to the EDS data.

The release processing does roughen the polysilicon on the top of structure. The average roughness went from R_a of 4.92±0.18 nm and R_q of 6.10±0.28 nm to a R_a of 7.55±0.13 nm and R_q of 9.57±0.11 nm for a poly2 upper surface on a MUMPs 36 chip. The average roughness went from R_a of 5.61±0.18 nm and R_q of 7.11±0.22 nm to a R_a of 7.07±0.37 nm and R_q of 9.03±0.74 nm for a poly2 upper surface on a MUMPs 37 chip. It is interesting to note that the MUMPs 37 surfaces were rougher than the MUMPs 36 ones prior to release but somewhat smoother afterwards. This may be due to a wax reaction with the photoresist during dicing for the MUMPs 36 die.

The CO_2 supercritical dry process produces polysilicon surfaces that are generally clean. The silicon nitride layer under the polysilicon flaps does have residues which need to be explored. There were some large residue droplets showing sodium and sulfur contamination in addition to fluorine residues. Also, several of the structures were broken during the CO_2 supercritical dry process, or more likely, transportation of the chip after drying.